



The structure of the Chañarcillo Basin: An example of tectonic inversion in the Atacama region, northern Chile

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ABSTRACT

The Chañarcillo Basin is an Early Cretaceous extensional basin in northern Chile (27–29°S). The folding style of the syn-rift successions along the eastern side of the basin reveals an architecture consisting of a NNE-trending anticline “Tierra Amarilla Anticlinorium”, associated with the inversion of the Elisa de Bordos Fault. A set of balanced cross sections and palinspastic restorations across the basin show that a partially inverted “domino-style” half-graben as the structural framework is most appropriate for reproducing the deformation observed at the surface. This inverted system provides a 9–14 km shortening in the basin. The ages of the synorogenic deposits preserved next to the frontal limb of the “Tierra Amarilla Anticlinorium” suggest that basin inversion occurred close to the “K–T” boundary (“K–T” phase of Andean deformation). We propose that tectonic inversion is the fundamental deformation mechanism, and that it emphasizes the regional importance of inherent Mesozoic extensional systems in the evolution of the northern Chilean Andes.

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RESUMEN

La Cuenca Chañarcillo, es una cuenca originalmente extensional de edad cretácica temprana ubicada en la región norte de Chile (27–29°S). Las series sin-rift de su extremo oriental, se encuentran envueltas en un anticlinal de orientación NNE, el “Anticlinorium de Tierra Amarilla”, que ha sido asociado con la inversión de la falla Elisa de Bordos. Las diversas secciones balanceadas y restauradas, construidas a través de la cuenca muestran como un arreglo estructural de hemi-grabenes en “domino” parcialmente invertidos, constituye el escenario más favorable para reproducir la deformación de superficie. Este arreglo estructural, aporta un acortamiento para la cuenca, que varía entre 9 km a 14 km. Por otro lado, los depósitos sinorogénicos preservados cerca del limbo frontal del “Anticlinorium de Tierra Amarilla”, permiten interpretar que la inversión ocurriría cerca del límite de deformación andina “K–T”. Considerando lo anterior, se propone a la inversión tectónica como un mecanismo de deformación dominante, resaltando la importancia de los sistemas extensionales mesozoicos en la evolución de los Andes del norte de Chile.

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1. Introduction

The tectonic evolution of the Central Andes was dominated by different episodes of crustal stretching and shortening, which derived from complex geodynamic processes related to the oceanic plate subduction beneath the western South American continental

margin from the Early Jurassic to present (Daziel et al., 1987; Mpodozis and Ramos, 1990; Aguirre-Urreta, 1993; Scheuber et al., 1994; Mpodozis and Allmendinger, 1993; Ramos, 2010). A widespread extension related to the Late Permian–Early Triassic continental fragmentation of southwest Gondwana allowed the formation of rift systems.

The continuous kinematics of the retreating subduction, coeval with the break-up of Pangea–Gondwana originated a progressive stretching of the upper crust, establishing a magmatic arc with extensional backarc basins on the eastern side, which are characterized by half-graben architectures along the continental margin.

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These tectono-structural kinematic adjustments occurred during Late Jurassic–Early Cretaceous time, related to the beginning of the “Andean Cycle” (Coira et al., 1982; Mpodozis and Ramos, 1990; Franzese and Spalletti, 2001; Amilibia et al., 2008; Ramos, 2009).

Although the topography and thickness of this orogenic system have been explained by successive episodes of tectonic shortening and thickening of the continental margin (Isacks et al., 1988; Sheffels, 1990; Schmitz, 1994; Lamb and Hoke, 1997; McQuarrie and DeCelles, 2001), most authors have considered the progressive closure and tectonic inversion of previous rift basins as a mechanism to explain the mountain uplift in the region, starting as early as the Late Cretaceous–Early Paleocene (Isacks et al., 1988; Mpodozis and Ramos, 1990; Sheffels, 1990; Schmitz, 1994; Coney and Evenchick, 1994; Sempere et al., 1995, 1997; Lamb and Hoke, 1997; Horton and DeCelles, 1997; McQuarrie and DeCelles, 2001; Horton et al., 2001; Coutand et al., 2001; McQuarrie and DeCelles, 2001; Cobbold et al., 2007; Arriagada et al., 2006, 2008).

“Positive tectonic inversion” is a process occurring when basin-controlling extensional faults reverse their movement during compressional or transpressional tectonics, and, to varying degrees, basins are turned inside out to become positive features (Williams et al., 1989). This process is often assumed to occur by simple fault reactivation; however, several studies have shown that inverted structures can display complex geometries with pre-existing fault surfaces that can be truncated by, or reactivated as younger faults (Butler, 1989; Tavarnelli, 1996; Scisciani et al., 2002) (Fig. 1). On other hand, several factors affect the occurrence and style of inversion structures such as: fault orientation with respect to the stress regime and friction coefficient, fault geometry, pre-inversion geometry of the basin, and thermal state of the lithosphere at the time of inversion and plate-tectonic setting (Sibson, 1985; Butler, 1989; Buchanan and McClay, 1991; Ziegler et al., 1998; Mescua and Giambiagi, 2012).

Multiple mountain belts such as the Principal Cordillera in Argentina, the Apennines, the Pyrenees and the Mérida Andes in Venezuela, have been affected by previous rifting processes and tectonic inversion, so that inherent extensive features have controlled the subsequent development of the contractional structures confined within these orogenic systems (Dewey et al.,

1989; Butler, 1989; Bailey et al., 2002; Scisciani et al., 2002). Especially in the Central Andes, a series of NNW–SSE basins such as the Salta Rift, the Cuyo and Neuquén Basins have recorded the Mesozoic rift history and their subsequent tectonic inversion related with the Andean Orogeny (Maceda and Figueroa, 1995; Cristallini et al., 1997; Franzese and Spalletti, 2001; Cristallini et al., 2006; Carrera et al., 2006).

Recent structural interpretation from field observations and seismic data in basins and deformed belts in northern Chile such as the Salar de Atacama Basin, Cordillera de Domeyko, Tarapacá Basin, La Ternera Basin, and Lautaro Basin inter alia, indicate: i) the existence of at least two major extensional tectonic features composed of a set of NNW–SSE trending Triassic rift systems, and Early Jurassic–Early Cretaceous N–S trending backarc basins superimposed on the pre-existing Triassic basin, ii) a general stratigraphic continuity between the Late Triassic and the Early Cretaceous deposits, iii) the fact that the tectonic inversion of both NNE–SSW Jurassic–Early Cretaceous backarc basins and NNW–SSE Triassic rift systems, is a fundamental mechanism for the tectonic evolution of this region (Charrier, 1979; Urien et al., 1995; Mpodozis et al., 2005; Charrier et al., 2007; Amilibia et al., 2008; Martínez et al., 2012).

The NNW–SSE Triassic rift systems were strongly influenced by continental extension driven by the thermomechanical collapse of a Late Paleozoic thickened crust closely associated with pre-existing Paleozoic suture zones (Urien et al., 1995; Franzese and Spalletti, 2001; Amilibia et al., 2008). The regional extent and temporal evolution of the N–S Early Jurassic–Early Cretaceous sedimentary and volcanic record superimposed on the pre-existing Triassic were conditioned by the negative roll-back subduction along the western margin of Gondwana and the opening of the southern Atlantic Ocean (Franzese et al., 2003). By the end of the Early Cretaceous, the opening of the South Atlantic Ocean and the consequent separation of South America from Africa marked the start of contractional deformation and basin inversion in the southern Central Andes (Cobbold and y Rosello, 2003; Zamora Valcarce et al., 2006; Somoza and Zaffarana, 2008).

A case of special interest to recognize the geometries and effects of an Early Cretaceous backarc basin and the compressive

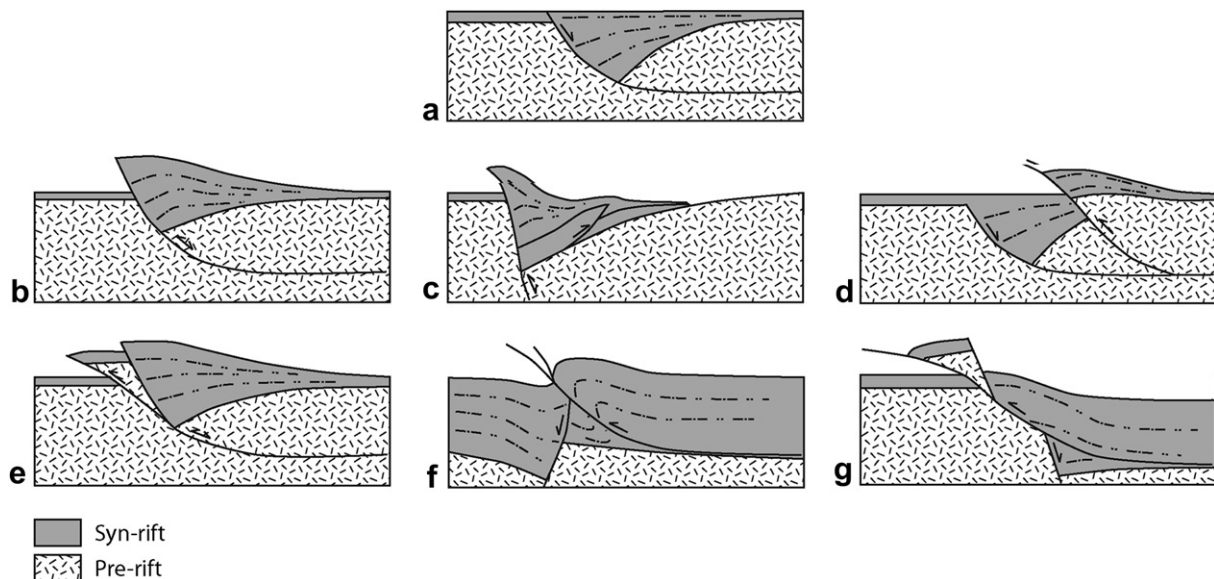


Fig. 1. Styles of interaction between previous extensional faulting and subsequent contractional structures, a) normal fault and rollover anticline, b) previous normal fault is reactivated as a “harpoon” style, c) partial reactivation of previous normal faults with buttress and backthrusting of the syn-rift successions, d) development of hanging-wall short-cut, e) development of footwall short-cut, f and g) folding and thrusting of previous normal faults (Modified from Scisciani et al., 2002).

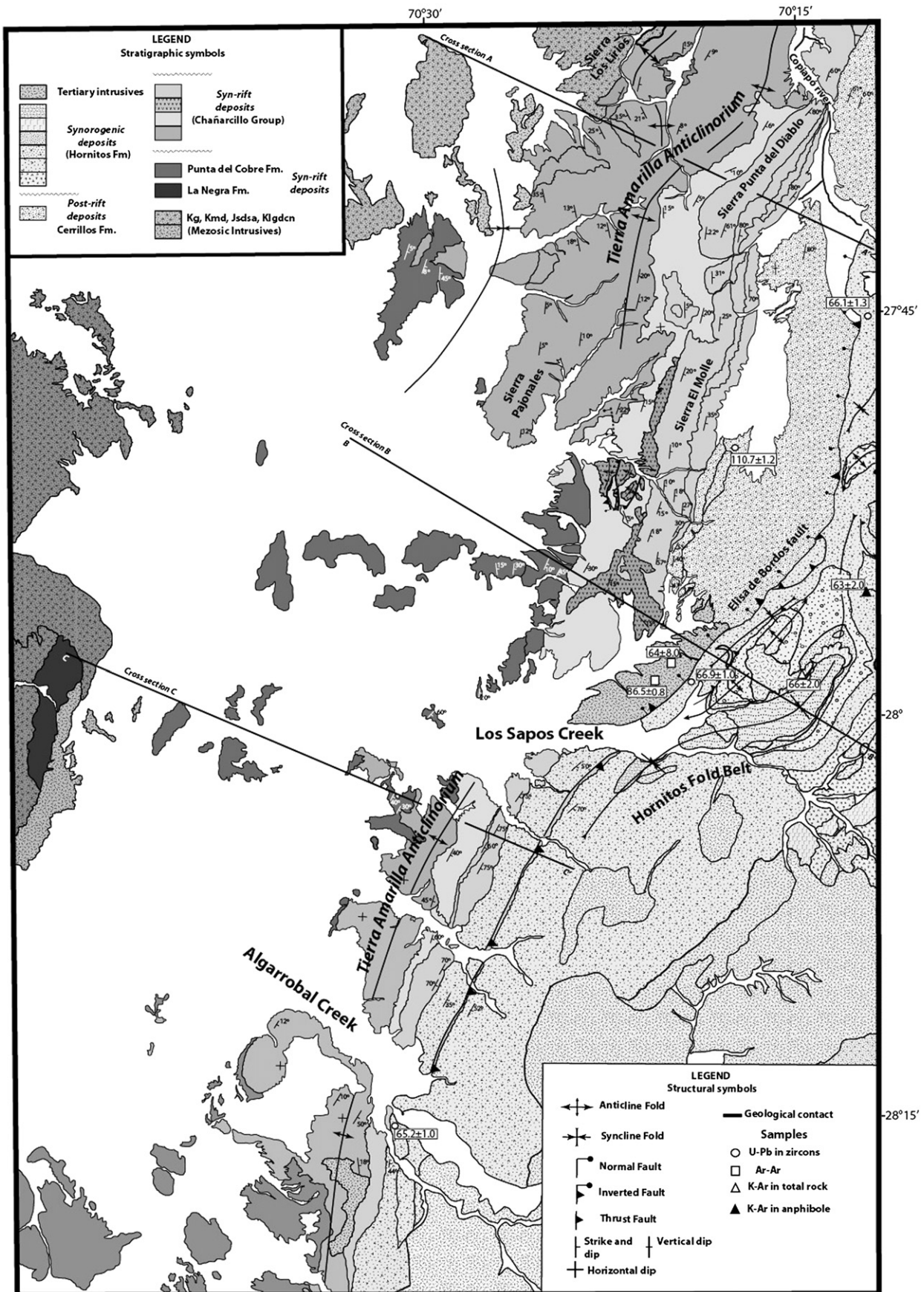


Fig. 3. Geological map of the Chañarcillo Basin. Scale 1:100,000; (modified from Arévalo, 2005b and Mourges, 2007).

Arévalo, 1999), different structural styles have been observed along the Chañarcillo Basin. The major structural geometries include extensional domino systems (Mpodozis and Allmendinger, 1993), a west-vergent fold-and-thrust belt (Arévalo and Mpodozis, 1991), evidence of sinistral transpression (Arévalo and Grocott, 1997) and a large east-vergent anticlinorium, the so-called “Antiformal Stack” (Tierra Amarilla Anticlinorium; Segerstrom, 1960; Arévalo and Mpodozis, 1991).

Until now, few tectonic models have considered the tectonic inversion of previous extensional fault systems as the result of a contractional process governed by the physical characteristics of the Mesozoic rift systems and the compression of the Andean margin in northern Chile. Although this relationship at that latitude is not clear, recent studies in adjacent regions (Cordillera de Domeyko and Lautaro Basin) show that these compressive structures have developed from tectonic inversion processes (Amilibia et al., 2008; Martínez et al., 2012).

In this contribution, we present the results of a detailed structural study, carried out along the Chañarcillo Basin, between the valley of the Copiapó River and the Donkey Creek, in the Atacama region of northern Chile (Fig. 3). After detailed mapping, we have synthesized the structural and stratigraphic information in a set of balanced and restored cross-sections, to better constrain the geometry, kinematics and shortening estimations of the area. In addition, the geochronological database available for the region was integrated with the structural interpretation to obtain the age of deformation. This investigation shows new evidence to explain the interaction between the Mesozoic rifting features and the compressive deformation observed in northern Chile.

2. Geological setting

The continental margin in the Atacama region between 27 and 30°S is located over the Pampean “Flat-Slab” segment of northern Chile and Argentina, where the Nazca Plate is subducted nearly horizontally beneath western South America (Fig. 2a, Jordan et al., 1983; Cahill and Isacks, 1992). From W to E, the major morpho-tectonic features, which are parallel to the coastline and the orogen are the Coastal Cordillera, the Frontal Cordillera, the Andean Precordillera and the Sierras Pampeanas (Fig. 2a).

In the Coastal Cordillera, significant Permo–Triassic plutonic complexes intruded Devonian to Carboniferous low-grade meta-sedimentary rocks (quartzites and metapelites); both represent at this latitude the pre-rift basement at the continental margin in northern Chile (Figs. 2b and 3; Bell, 1984; Naranjo and Puig, 1984; Bahlburg and Breitskreuz, 1993; Grocott and Taylor, 2002). This basement is mainly overlain by Triassic syn-rift series (e.g. Cifuncho and Agua Chica Formations), Jurassic volcanic rocks (e.g. La Negra and Punta del Cobre Formations) and Early Cretaceous syn-rift successions (e.g. Chañarcillo Group) (Naranjo and Puig, 1984; Suarez and Bell, 1992; Mpodozis and Kay, 1990; Grocott and Taylor, 2002).

Along the eastern edge of the Coastal Cordillera, thick successions of dacitic to calc-alkaline lavas and domes of the La Negra and Punta del Cobre Formations, derived from the Early Jurassic–Early Cretaceous magmatic arc (circa 192–125 Ma; Taylor et al., 2007), were developed during crustal extension of the continental margin. In this region, the Paleozoic pre-rift basement and volcanic and sedimentary Mesozoic syn-rift units were intruded by a suite of syn-extensional Jurassic and Cretaceous granitoid intrusives, which are restricted to the western Coastal Cordillera (e.g., the Coastal Batholith yields spectrum of ages from 190 to 90 Ma by K/Ar, Ar/Ar y U/Pb; Dallmeyer et al., 1996), growing progressively younger eastwards (Fig. 2b).

The oldest syn-rift series in the Chañarcillo Basin correspond to the Punta del Cobre Formation that consists of at least 1300 m of basaltic and basaltic-andesitic lava flows, volcanoclastic rocks and breccias (Marschik and Fontboté, 2001). These are unconformably overlain by up to 4 km of calcareous and siliciclastic deposits corresponding to the marine Valanginian–Aptian cycle of the Chañarcillo Group (Fig. 4; Segerstrom and Parker, 1959; Segerstrom, 1960; Segerstrom and Ruiz, 1962), which has been interpreted as a backarc syn-rift succession (Arévalo, 1999; Mourgues, 2004, 2007).

The Chañarcillo Group has been divided in to four conformable formations, which are from base to the top: the Abundancia, Nantoco, Totoralillo and Pabellón Formations (Fig. 4; Biese in Hoffstetter et al., 1957). The Abundancia Formation consists of around 200 m of gray mudstone and arkoses with *Olcostephanus* (*O*) aff. *atherstoni* (Sharpe), *Olcostephanus* (*O*) aff. *densicostatus* (Wegner), *Olcostephanus* (*V*) *permolestus* (Leanza), and other marine fauna of late Valanginian age (Corvalán, 1973; Segerstrom and Ruiz, 1962).

The Nantoco Formation is a conspicuous unit with a thickness of about 1200 m of gray mudstone, wackestone, evaporitic minerals and calcareous breccias with *Crioceratites* (*C*) *schlagintweiti* (Giovine), which have been interpreted as supratidal deposits accumulated during the Hautevirian. The Nantoco Formation is overlain by 180–300 m of yellow and pink marls with *Crioceratites* (*Paracrioceras*) cf. *emerici* Levillé and *Shastrioceras* cf. *Poniente* of late Barremian age corresponding to the Totoralillo Formation. The Pabellón Formation represents 2100 m of a mixed sedimentary and volcanic succession of late Barremian–Aptian age with a fauna consisting of *Parancyloceras?* *domeykanus*, *Prahoplites* gr. *nutfieldi* *diensis*, *Paulkella nepos* (Paulcke) (Perez et al., 1990; Mourgues, 2004, 2007; Arévalo, 2005). Both to the north–west and south, deposits of the Chañarcillo Group interfinger laterally with terrestrial volcanoclastic rocks of the Bandurrias Formation (Segerstrom and Parker, 1959; Segerstrom, 1963; Marschik and Fontboté, 2001), forming a NNE-trending belt of about 200 km in length (Fig. 3) between the eastern Coastal Cordillera and the western Frontal Cordillera in northern Chile.

On the other hand, about 4000 m of conglomeratic and volcanoclastic series defined as the Cerrillos Formation, unconformably overlie the upper section of the Chañarcillo Group (Figs. 3 and 4) (Segerstrom and Ruiz, 1962; Jensen, 1976; Jensen and Vicente, 1976; Arévalo, 1995; Marschik and Fontboté, 2001; Arévalo, 2005a,b). This unit represents a clastic wedge with U/Pb ages between 110.7 ± 1.7 and 99.7 ± 1.6 Ma in the lower part and up to 69.5 ± 1.0 Ma in the upper part (Maksaev et al., 2009). The continental sedimentation and coeval subaerial volcanism of this post-rift succession mark an abrupt change from previous syn-rift marine carbonate sedimentation within the backarc setting (Segerstrom and Parker, 1959; Zentilli, 1974; Jurgan, 1977; Perez et al., 1990; Arévalo, 2005a,b). However, some authors have interpreted a synorogenic origin for this deposit related to a foreland basin (Maksaev et al., 2009), but there is no clear evidence for a mountain front between the oldest Chañarcillo Group and the Cerrillos Formation.

Unconformably overlying the Cerrillos Formation, a succession of sediment, lavas and ignimbrites belonging to the Hornitos Formation (Fig. 4) (Arévalo, 1994; Cornejo and Mpodozis, 1996) are coeval with the magmatic arc migration to the east of the Coastal Cordillera at about 85 Ma (Mpodozis and Ramos, 1990). These Late Cretaceous deposits are covered by a string of Paleocene–Eocene volcanic complexes, which include rhyolitic domes and several collapsed calderas, formed after a major compressive deformation event that took place around the Cretaceous–Tertiary transition, in the western margin of the Central Andes (Cornejo et al., 1993).

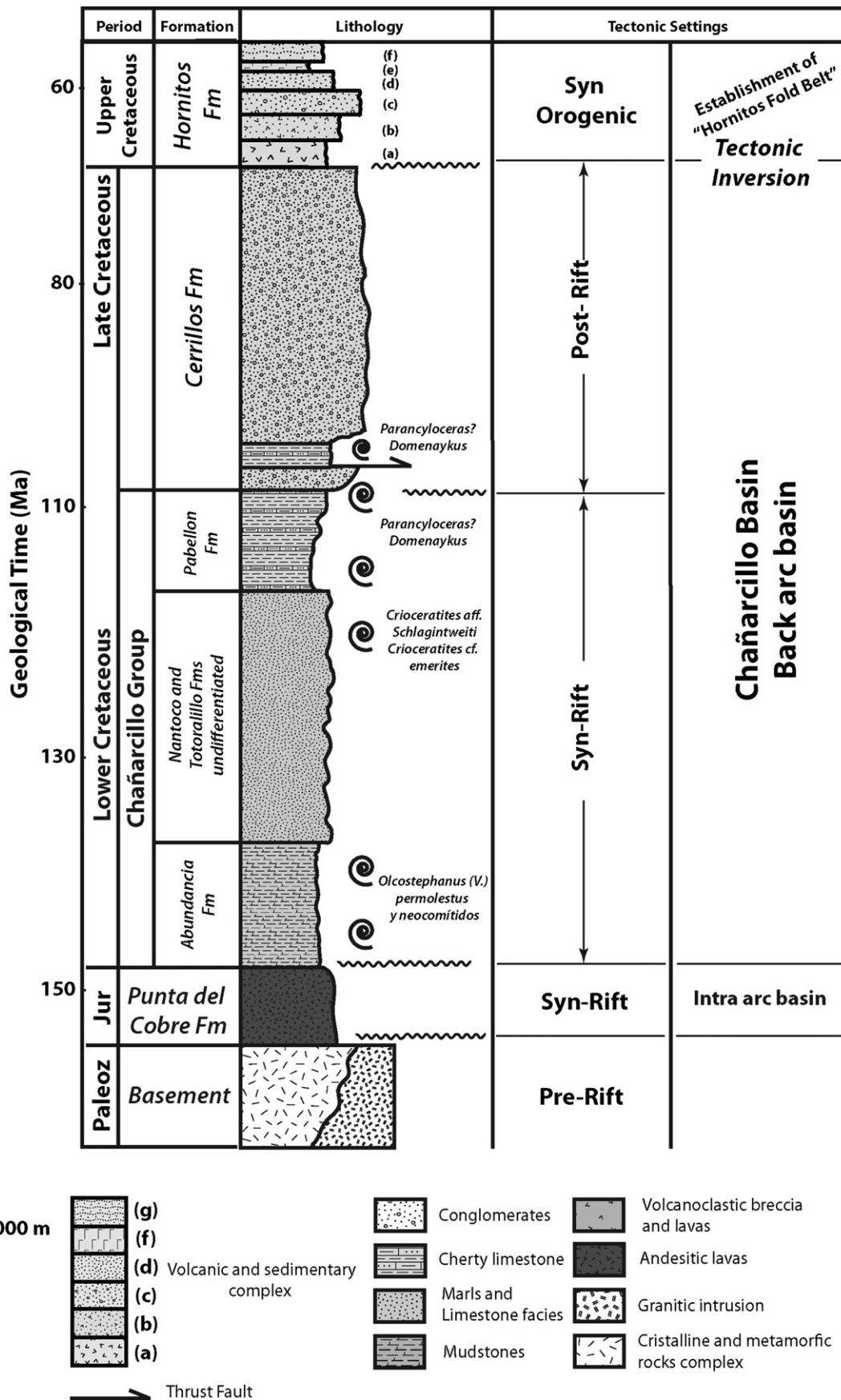


Fig. 4. Generalized of the stratigraphic column based on previous studies (Seegerstrom and Ruiz, 1962; Mourgues, 2004) and our observations.

3. Basin structure

Excellent exposures of Neocomian marine successions are found within the Chañarcillo Basin. The tectonic features affecting the basin infill include the large sinuous southeast-vergent anticline “Tierra Amarilla Anticlinorium” defined by Segerstrom (1960) extending along a NNE strike over 200 km from the Copiapó Valley to the Santa Juana Reservoir on the Tránsito Valley (Figs. 2 and 3). Northwards, in the Sierra Punta del Diablo, next to the Copiapó River valley (Fig. 3), the anticline has an asymmetrical, overturned, east-vergent geometry that affects both the Chañarcillo Group and the Cerrillos Formation (Fig. 5a). Toward the west of the anticlinorium the back limb of the fold is almost flat-laying (Fig. 5a; Arévalo et al., 2006). Arévalo et al. (2006), recognized low-angle west-vergent faults (e.g. The Cerrillos Detachment of Arévalo et al., 2006) which are internally detaching the Chañarcillo Group and can be interpreted as accommodation faults during the growth of the “Tierra Amarilla Anticlinorium”.

Large variations in the stratigraphic thickness of the Chañarcillo Group occur between the frontal and back limbs of the Tierra Amarilla Anticlinorium. While over the back limb the marine deposits of the Chañarcillo Group have a thickness of less than 1000 m, at the frontal limb they are up to 2000 m thick, defining a wedge geometry for the Chañarcillo Group deposits. On the other hand, the up to 4000 m thick volcanoclastic deposits of the

Cerrillos Formation have only been observed in the frontal limb of the Tierra Amarilla Anticlinorium (Fig. 3), which is truncated by a master fault toward the east (Fig. 5b) that controlled sedimentation both for the Chañarcillo Group and the overlying Cerrillos Formation.

Along the Sierra El Molle, the Chañarcillo Group shows structural features including growth wedges and normal faulting that suggest an extensional tectonic regime during deposition (Fig. 6). Synsedimentary normal faults, slumps, and olistostromes within the lower and upper series of the Chañarcillo Group, associated with shelf collapses were identified by Mourgues (2004). North of the Copiapó River, in the Puquios area, Mpodozis and Allmendinger (1993) reported low-angle normal faults, which they associated with extensional tectonics during the Early Cretaceous.

The fact that the region formerly occupied by the Chañarcillo Basin, has become a positive structural relief consisting of the large asymmetrical “Tierra Amarilla Anticlinorium”, suggests that the structural style of the region can be defined as a classical harpoon anticline (Fig. 7a and b) linked to inversion tectonics (McClay and Buchanan, 1992). To the east of the basin, this structure is truncated by the high-angle N–S to NNE-oriented Elisa de Bordos Fault that runs almost parallel to the main trend of the harpoon structure of the Chañarcillo Basin or “Tierra Amarilla Anticlinorium” (Figs. 3 and 5). The Elisa de Bordos Fault can be traced from south of the Copiapó River to Sapos Creek, and marks the contact between the

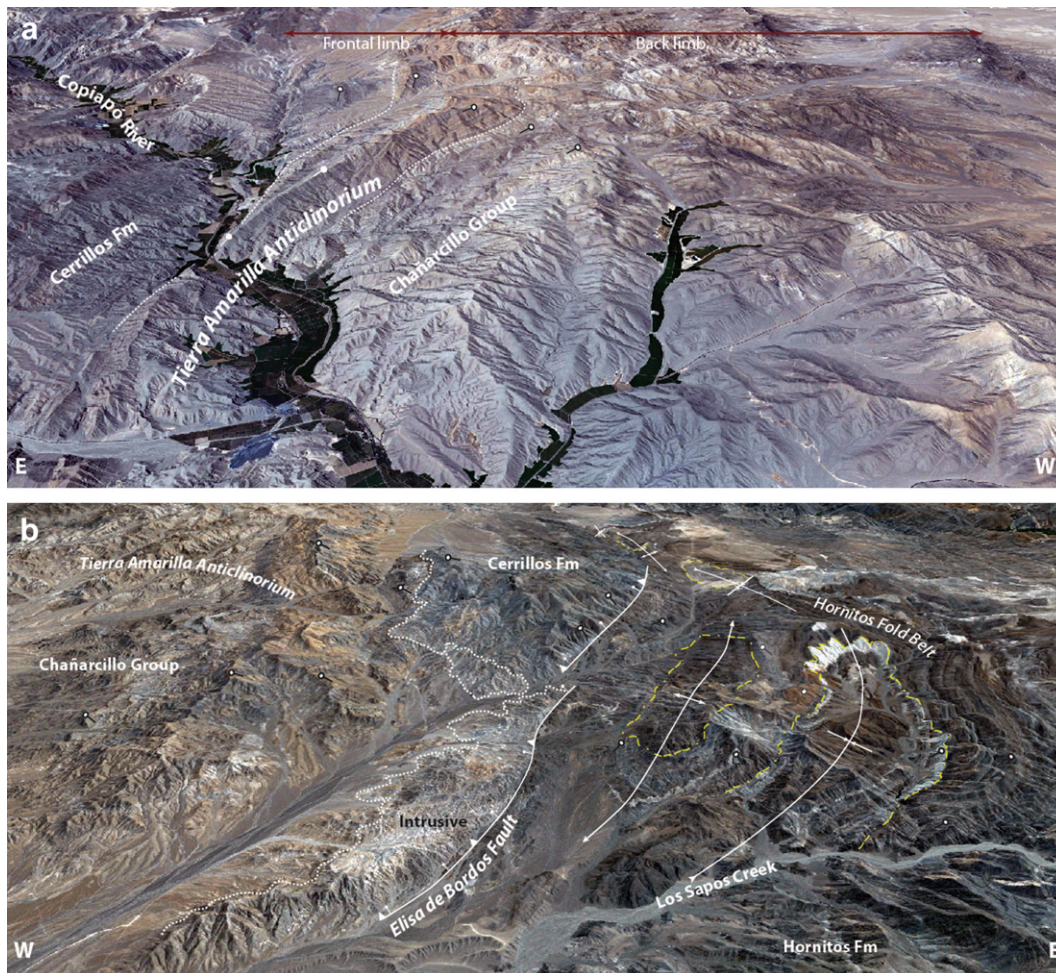


Fig. 5. Satellite images indicating: a) E–W panoramic view of the syn-rift Neocomian successions involved in the “Tierra Amarilla Anticlinorium” in the Sierra Punta del Diablo region, north of the Copiapó River (see Fig. 3), b) W–E panoramic view of the Elisa de Bordos Fault, which emplaced the asymmetrical anticline “Tierra Amarilla Anticlinorium” over the “Hornitos Fold Belt” at the Los Sapos Creek (see Fig. 3).

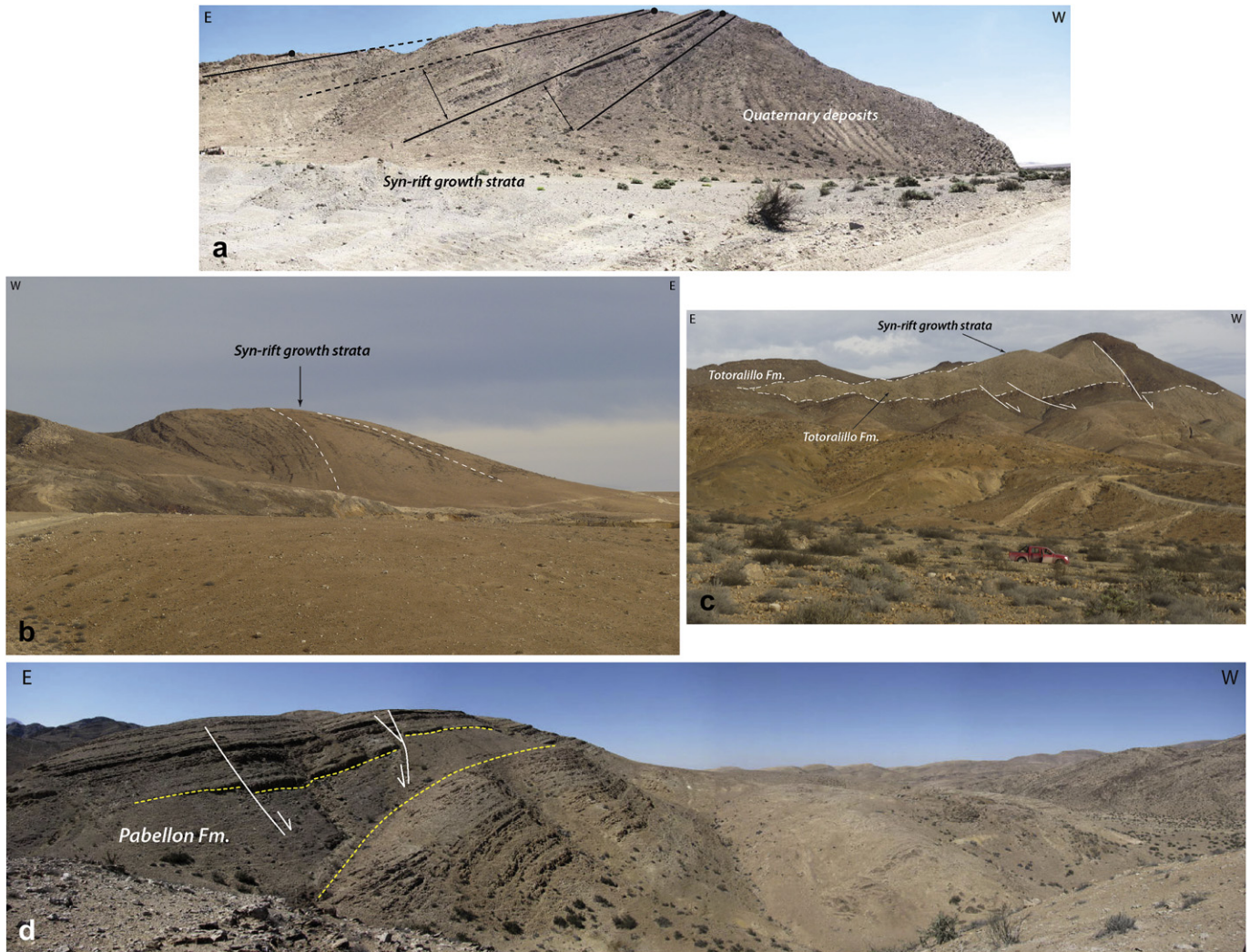


Fig. 6. Example of extensional features recognized within mid-upper sections of the Chañarcillo Group, a–c) growth strata, c–d) syn-extensional faulting.

Cerrillos Formation and the doubly-vergent synorogenic “Hornitos Fold Belt” (Figs. 3, 5 and 8a; Segerstrom and Ruiz, 1962; Segerstrom, 1963; Arévalo, 2005a,b; Peña et al., 2010), which forms a 60 km long and 30 km wide swath immediately east of the Elisa de Bordos Fault. In plan view, the sinuous shape of the axis of the “Tierra Amarilla Anticlinorium” is closely related to the trace of the Elisa de Bordos Fault. These structural features are very similar to those described in analog models of inverted oblique and offset rift systems (Amilibia et al., 2008), suggesting the occurrence of NE–SW oriented offsets along the main border, at least, along the eastern side of the Chañarcillo Basin.

The Hornitos Fold Belt includes the Late Cretaceous–Paleocene volcanic–sedimentary successions of the Hornitos Formation and kilometer-scale thin-skinned anticlinal ridges and synclinal valleys as well as well-developed NE–SW patterns of asymmetrical folds related to imbricated thrusts (Fig. 8b). In plan view, immediate to the footwall of the Elisa de Bordos Fault, a series of NNE–SSW-striking *en echelon* doubly plunging fold axes also affecting the Hornitos Formation (Figs. 3 and 5b; Arévalo, 2005b) indicate right-lateral transpression. Stratigraphic patterns such as growth strata in deposits within large synclines (Fig. 8c) of the Hornitos Formation implicate syntectonic sedimentation during the contractional event that formed the Chañarcillo Basin and thrusts the “Tierra Amarilla Anticlinorium” eastward over the Late Cretaceous–Paleocene

strata. This event could also have caused the uplift of the Coastal Cordillera at this latitude.

4. Balanced cross sections and palinspastic restorations

4.1. Methodology

The main structural relationships previously described were analyzed further by constructing three regional cross-sections (Fig. 3), of 27.96 km, 56.13 km, and 33.90 km length (Fig. 9), distributed along the Chañarcillo Basin with a WNW–SSE preferential orientation (Fig. 3), all of them perpendicular to the axis of the “Tierra Amarilla Anticlinorium” and parallel to the direction of the tectonic transport. The western side of the cross-sections includes previous geological data from Arévalo and Mpodozis (1991), Mourgues (2004), Arévalo (2005b), and Arévalo and Welkner (2008), whereas the central and eastern parts are supported by our own new results.

The original sections were constructed by hand at 1:50,000 and 1:100,000 scales, considering dip angles of the strata, the thickness of the stratigraphic unit, and the predominant structural style. Balanced and palinspastic-restored cross-sections were simulated using the computer program, 2D-MOVE (Midland Valley). This procedure was performed assuming a plain strain, and using

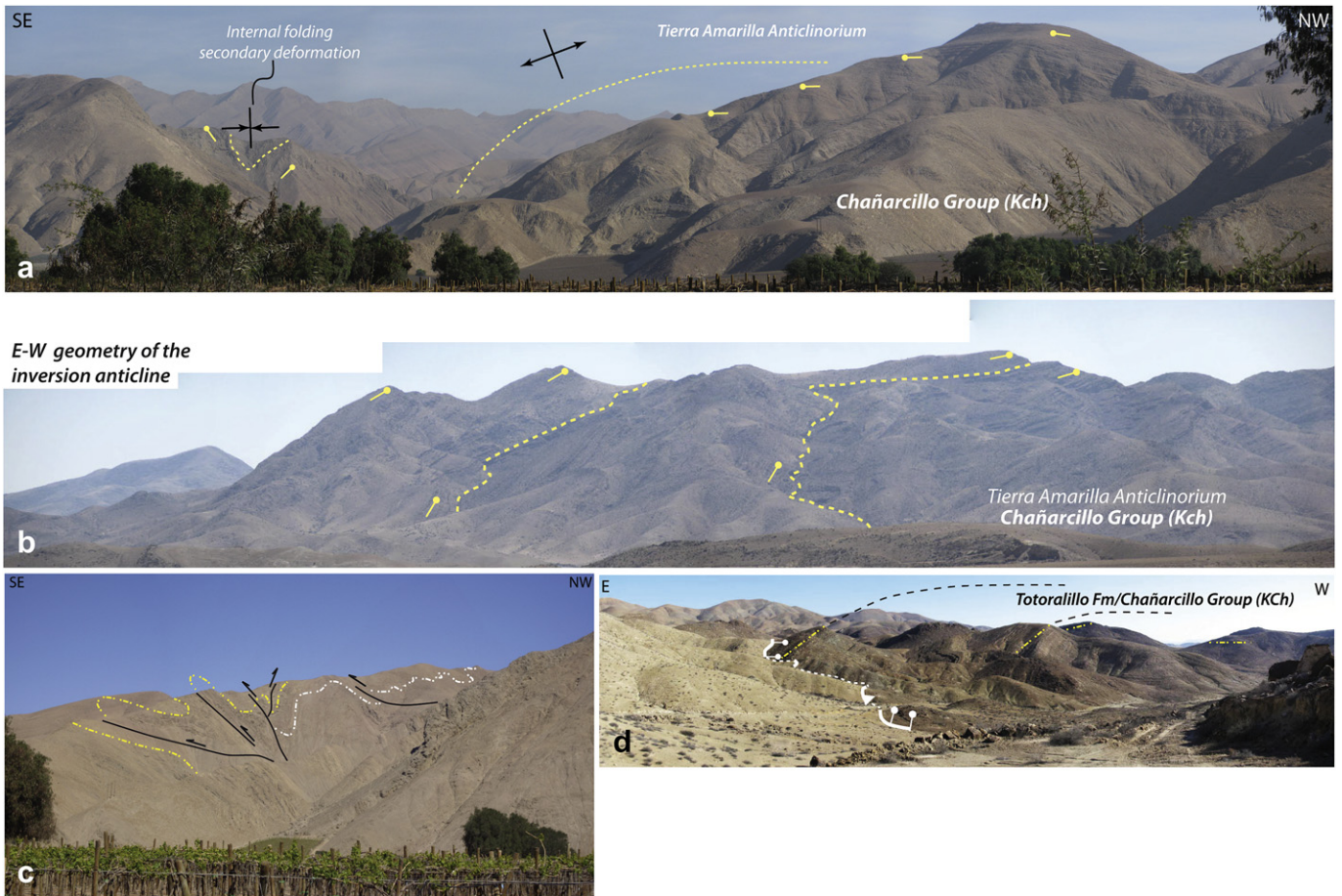


Fig. 7. a) Asymmetrical anticline "Tierra Amarilla Anticlinorium" observed in the Sierra Punta del Diablo location, north of the Chañarcillo Basin (see Fig. 3), b) "Harpoon style" inversion anticline geometry observed across the Sierra El Molle in the central region of the Chañarcillo Basin, c) minor thrusting and folding within the upper and ductile layers of the Chañarcillo Group (Pabellón Formation), d) minor inverted fault within the Chañarcillo successions.

several algorithms to model the geometry and kinematics of each analyzed structure. The "fault-parallel flow" combined with "inclined shear" algorithms were used to restore thick-skinned compressional structures, while "flexural slip" and "length line" algorithms were used to restore the thin-skinned deformation developed in the Cenozoic synorogenic deposits.

4.2. Deep structure of the Chañarcillo Basin

Development of inversion anticlines has been traditionally explained by the fault propagation and folding mechanism. This has been widely recognized in blind structures and analog models (Brun and Nalpas, 1996; McClay, 1992; Yamada and McClay, 2003; Gomes et al., 2006). However, in our case, inversion of pre-existing normal faults cannot reasonably reproduce some geological characteristics within the "Tierra Amarilla Anticlinorium", such as the large subhorizontal back limb of the anticline, the absence of the basement at the surface, the long wavelength of the anticline, the lack of a master fault to the south of the basin, and the thin-skinned deformation observed in the frontal anticline, involving the Hornitos Fold Belt. In consequence, a flat-ramp-flat-ramp structure is needed to model both the inversion anticline and the Hornitos Fold Belt (Fig. 9). In this scenario, the east-vergent Elisa de Bordos Fault (Fig. 9a and b) represents the NNE upper ramp that dies out, at least at the surface, along the Los Sapos Creek, and appears to control the locations of NNE-striking Tertiary intrusive bodies. To the south of this creek, a thin-skinned back-thrust cuts

through both the Chañarcillo Group and the Hornitos Formation (Figs. 3 and 9c).

After a trial and error procedure with the 2D Move program we obtained a model consisting of listric faulting defined by partially inverted half-grabens ("domino model") coupled with an upper detachment (Fig. 9). This main structural framework is necessary to reproduce the structural features observed at surface. According to our modeling, the basal detachment is at about 9 km depth, which could be located within ductile units underneath the western Coastal Cordillera (e.g., the Chañaral Mélange and the Las Tórtolas Formation; Bell, 1984), with a ramp geometry that dips 45–50°W (Fig. 9). A hypothetical basal detachment of 9 km is needed to better reproduce the anticline geometry of the "Tierra Amarilla Anticlinorium". A shallower detachment does not reproduce the inversion anticline well and exposes the basement in the core of this anticline, which is not the observed case. On the other hand, deeper detachment causes excessive uplift (more than 3–4 km) of the Coastal Cordillera during the inversion.

Some inverted structures such as the Sierra Azul anticline in the Malargüe Fold-and-thrust Belt (Dicarlo and Cristallini, 2007; Yagupsky et al., 2007; Yagupsky et al., 2008; Giambiagi et al., 2008, 2009), the Pampa-Tril Anticline in the Neuquén Basin (Uliana et al., 1995) and the inverted ramp of the Cameros Basin in the Iberian chain (Guimera et al., 1995) inter alia, were derived from positive tectonic inversion of previous Mesozoic extensional systems (e.g., half-grabens, rollovers, extensional ramps). They have a geometry similar to the fault-bend-fold of the Chañarcillo Basin, but with

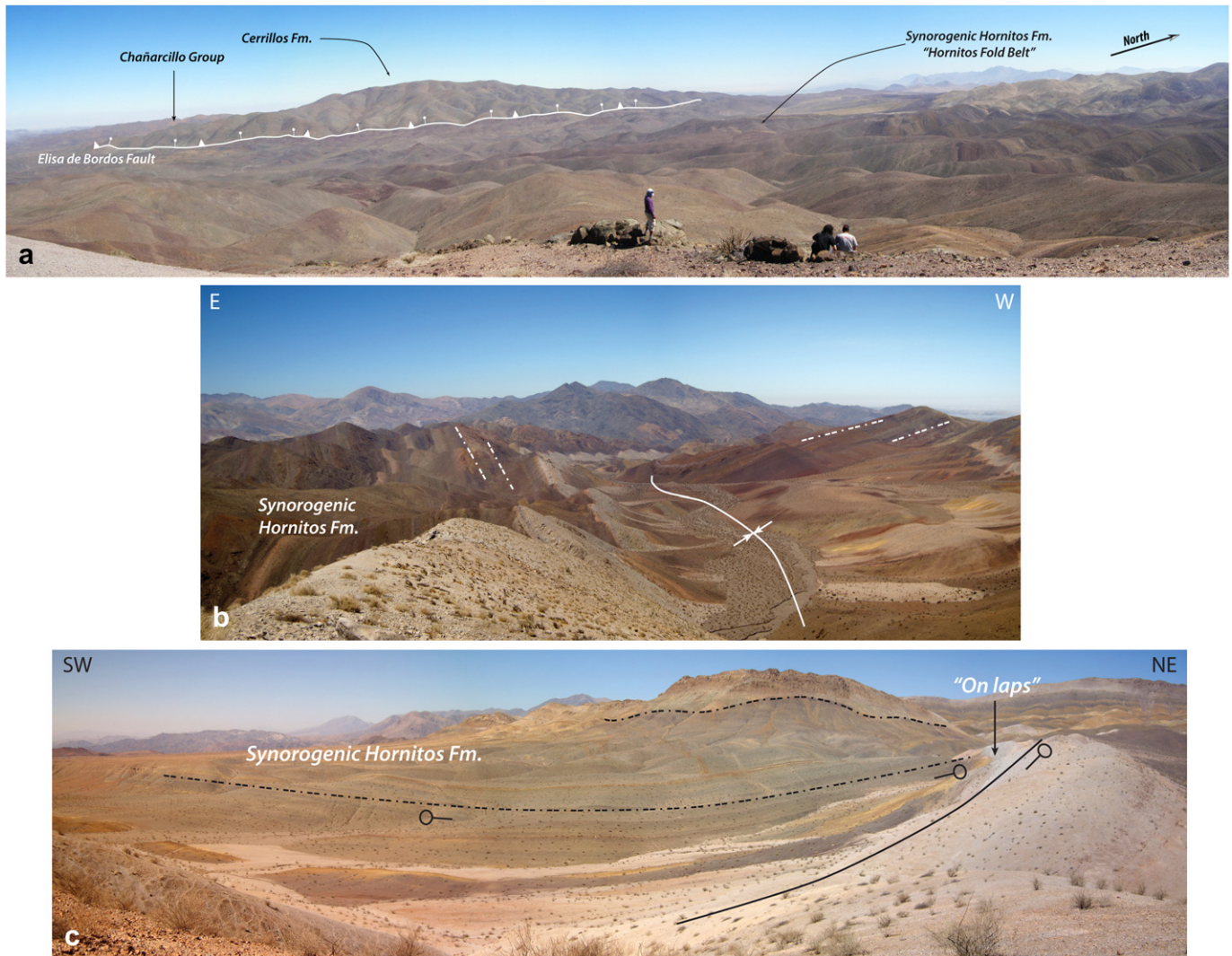


Fig. 8. a) Aspect of the positive relief on the hanging-wall block of the Elisa de Bordes Fault, b) thin-skinned structures recognized in the “Hornitos Fold Belt” c) details of the onlap architecture and progressive unconformities observed within the synorogenic Hornitos Formation.

different stratigraphic units and facies associated within their internal architecture. Another important characteristic of this structure is the transition of the ramp to the upper detachment, which allows the partial inversion and tilting of the rollover anticlines that are confined to their back limb, as observed across the balanced cross-sections (Fig. 9).

The balanced cross-section A–A' (Fig. 9a), constructed across the Sierra Punta del Diablo, shows that the upper Chañarcillo Group (Pabellón Formation) and Cerrillos Formation have been expelled from the basin. Several structures in this section have been related to the positive tectonic inversion process. A small-scale, west-vergent thin-skinned fold-and-thrust belt can be observed along the frontal limb, especially in the ductile upper section of the Chañarcillo Group (Fig. 7c). It is composed of disharmonic and tight folds related to minor thrusting that accommodate the compression in the frontal limb. Additionally, a long-wavelength anticline in the back limb of the “Tierra Amarilla Anticlinorium” is associated with a west-vergent, thick-skinned back thrust (Fig. 8a), developed in spite of the tilting and compression of the pre-rift basement along the Elisa de Bordes Fault. West of the anticline, several Cretaceous intrusives of 108 ± 3 Ma (K/Ar; Arévalo, 2005b), 109 ± 3 Ma (K/Ar; Arévalo, 1994), 109.8 ± 3.4 Ma (K/Ar; Zentilli,

1974) ages prevail in this region. In agreement with Arévalo (1994), Arévalo and Welkner (2008) and recently Grocott et al. (2009), we consider that the extensional basin architecture controlled the emplacement of these bodies (Fig. 9a).

Even though the frontal limb of the “Tierra Amarilla Anticlinorium” can be recognized all along the study area, some important changes occur to the south, especially in the back limb. A close inspection of Fig. 3 shows that an important variation of dip in the structural panels occurs within the Jurassic Punta del Cobre Formation. The same occurs in cross sections B–B' and C–C', although it is difficult to determine in them the subsurface structure controlling the deformation observed within the Jurassic units, which were reasonably modeled assuming a set of partially inverted half-grabens (Fig. 9b and c).

The eastern portion of the study area is characterized by intense folding within the synorogenic deposits of the Hornitos Formation (Fig. 3). Their structural style varies with the degrees of inversion in Chañarcillo Basin and the development of different thrust systems to the north and south of the Los Sapos Creek. North of the creek the thrust systems consist of an east-vergent thin-skinned thrust fault propagated from the Elisa de Bordes Fault, and a west-vergent, blind thick-skinned sheet that propagated through detachments

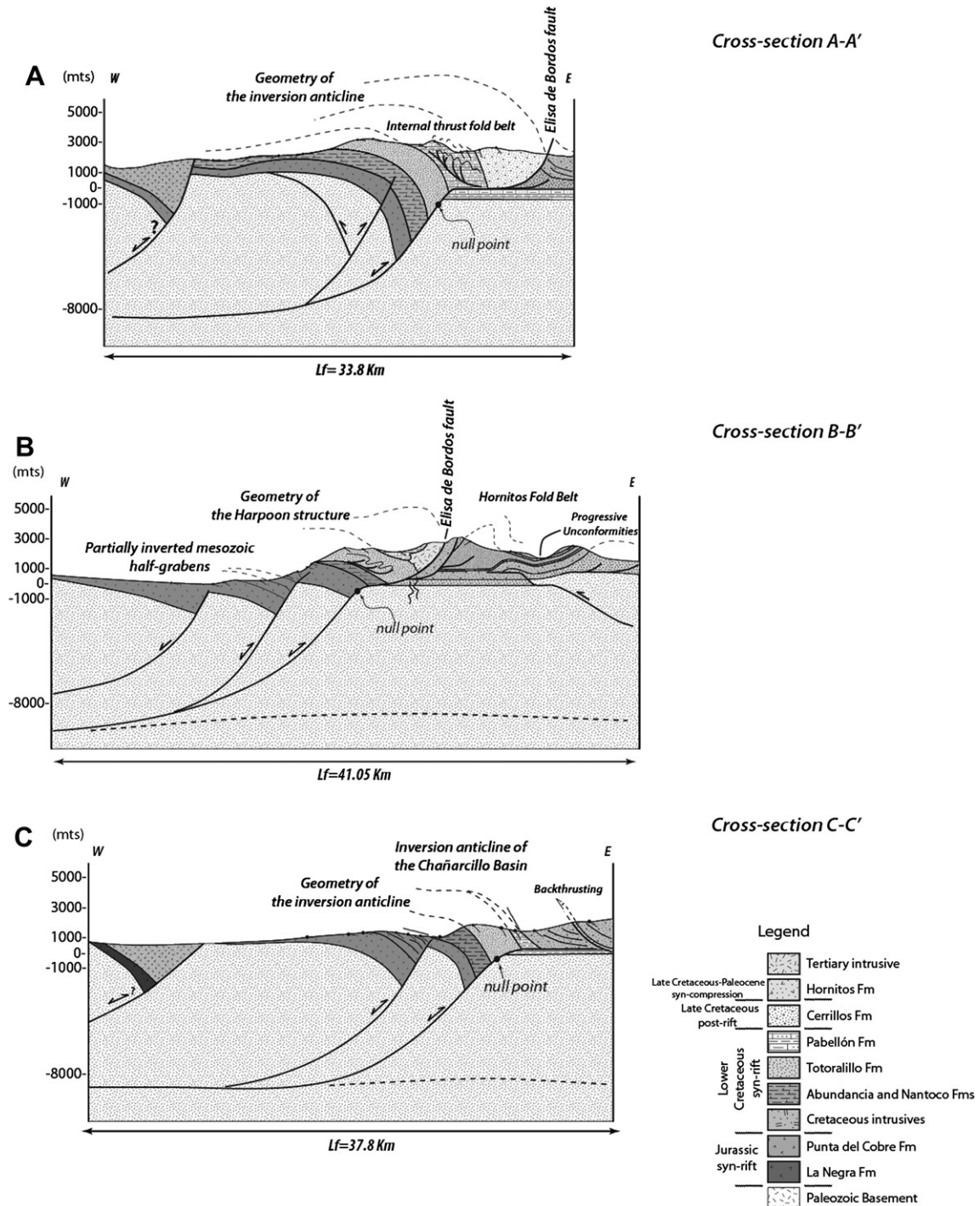


Fig. 9. Balanced cross-sections elaborated in this study. A–A', B–B' and C–C' correspond to north, central and south balanced cross-sections (see explanation in the text).

and ramps, which can have a tip point near the Elisa de Bordos Fault (Fig. 9b), and which might be associated with the west-vergent inversion of the Jurassic extensional Lautaro Basin (Martínez et al., 2012). South of the creek there is a west-vergent, thin-skinned back thrust coupled with the upper detachment of the Tierra Amarilla Anticlinorium (Fig. 9c).

The palinspastic restoration shown in Fig. 10 reveals for the Chañarcillo Basin a western dip-slip, half-graben geometry, which is related to the Early Cretaceous (Barremian) maximum extension. From this restoration (pre-shortening) the measurements of accumulated shortening are 7.5 (18%), 9.27 (18.42%) and 10.65 km

(21.98%) for sections A–A', B–B' and C–C' respectively (Fig. 10). These measurements are not exact because some data are not fully constrained in this region, such as the basal detachment location, the emplacement depth of Mesozoic intrusive units and some syn-rift Triassic-Jurassic stratigraphic thicknesses.

5. Age of deformation

Since the Late Cretaceous the tectonic evolution of the central Andes has been characterized by several contractional events separated by periods of relative quiescence or modest extension. The

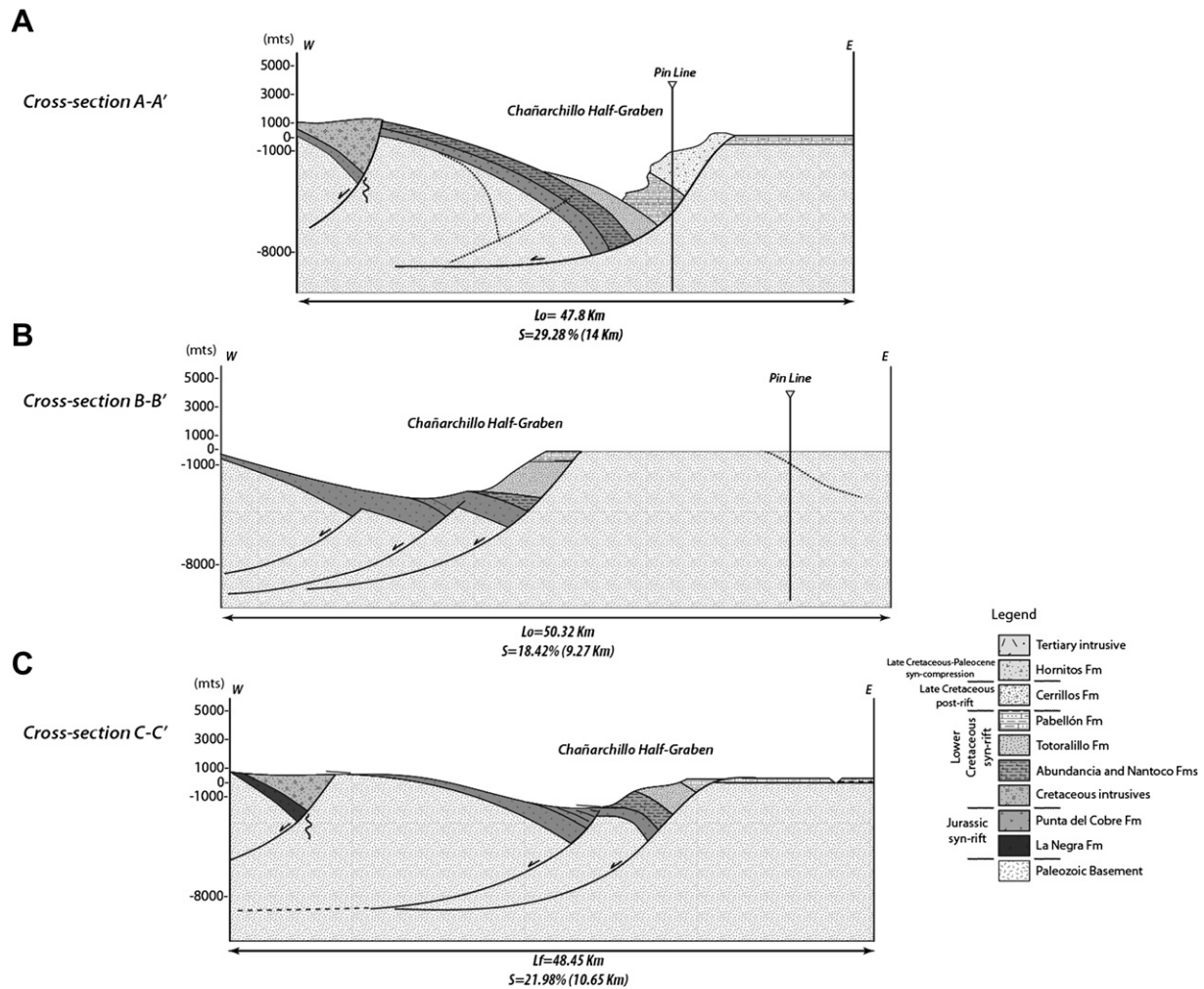


Fig. 10. Palinspastic restorations (“pre-shortening”) of the balanced cross-sections.

seminal work of Steinman (1929) established three regional shortening phases of deformation in Peru, the Peruvian (Late Cretaceous), Incaic (Paleogene) and Quechua (Neogene to recent) phases, which have been largely documented along the Central Andes.

Several authors have suggested that the compressional structure in the Chañarcillo Basin occurred during a time interval constrained by the emplacement of the Coastal Cordillera plutonic complexes (ca. 93 Ma) and the deposition of the Late Cretaceous Hornitos Formation at about 65 Ma (Arévalo and Grocott, 1997; Arévalo, 1999; Makshev et al., 2009). The age of the Hornitos Formation is the key to an upper limit for the age of deformation of the Chañarcillo Basin. Along the Algarrobal Creek, Makshev et al. (2009) obtained a U–Pb zircon age of 65.2 ± 2 Ma (Fig. 3) from lavas belonging to the Hornitos Formation, which lie in angular unconformity on the frontal limb of the inversion anticline.

Moreover, the occurrence of synorogenic deposits preserved on top of the Cerrillos Formation in the frontal limb of the “Tierra Amarilla Anticlinorium” and within the Hornitos Fold Belt (Fig. 3) indicates that the evolution of deformation of the Chañarcillo Basin occurred, at least partly, simultaneously with the accumulation of the Hornitos Formation about 65 Ma ago. In this context, the age of the inversion of the Chañarcillo Basin can be linked to the “K–T” compressive event recognized in the northern Chilean Andes as a short episode of deformation, between 62 and 65 Ma, which caused an angular unconformity between uppermost

Cretaceous and Paleocene volcanic successions (Cornejo et al., 1997, 2003).

6. Implications of the structural model

Although Mesozoic extensional deformation along the Central Andes has been widely accepted (e.g. Mpodozis and Ramos, 1989; Suarez and Bell, 1992; Mpodozis and Allmendinger, 1993; Franzese and Spalletti, 2001; Charrier et al., 2007; Amilibia et al., 2008; Ramos, 2009), the internal architecture of the main rift systems has been well documented in only a few regions. The best examples can be found in the NE–SW, NW–SE rift systems of Salta and Neuquén in Argentina (Cristallini et al., 1997; Franzese and Spalletti, 2001; Cristallini et al., 2006; Carrera et al., 2006). Extensional structures within these systems have been obliterated or obscured by the superimposed Peruvian, Incaic, K–T and/or Quechua compressive phases.

Even though there are good examples of extensional structures in neighboring regions (Mpodozis and Allmendinger, 1993), the rift system geometry has been inferred essentially from indirect evidence such as the distribution of several thousand meters of marine carbonate and terrigenous packages and a huge volume of tholeiitic and calcalkaline magmatic rocks coeval with the infilling by marine deposits (e.g. Charrier et al., 2007). Our field data from the Chañarcillo Basin in the western present-day Coastal Cordillera

provide information on the Cretaceous extension, the relative timing of the basin inversion and general Andean deformation styles.

A regional tectonic evolutionary sequence is summarized in Fig. 11. We propose that, at least at this latitude, the Chañarcillo Basin was structurally controlled by a west-dipping half-graben basement array possibly developed along weakness zones from the early Mesozoic extension. Subsequently, the Punta del Cobre Formation, Chañarcillo Group and Cerrillos Formation were accommodated within this domino style geometry, active between Jurassic and Late Cretaceous times. Shortening and tectonic inversion of previous extensional features caused the exhumation and growth of the huge east-vergent “Tierra Amarilla Anticlinorium”

most probably during the “K–T” compressional phase as suggested by the synorogenic deposits in the Hornitos Formation located unconformably above the Cerrillos Formation along the frontal limb of the “Tierra Amarilla Anticlinorium”. Shortening estimates for the Chañarcillo Basin range between 9 and 14 km (Fig. 10).

Based on the evidence for extensional features in the Chañarcillo Group and the folding of the syn-rift successions, the structure of the region is interpreted as the result of the inversion of normal Cretaceous faults. Consequently, the synorogenic volcanoclastic deposits of the Hornitos Fold Belt located to the east of the “Tierra Amarilla Anticlinorium” are closely related to this process.

Our model supports and reproduces the large “Tierra Amarilla Anticlinorium” as an inversion anticline and is also consistent with

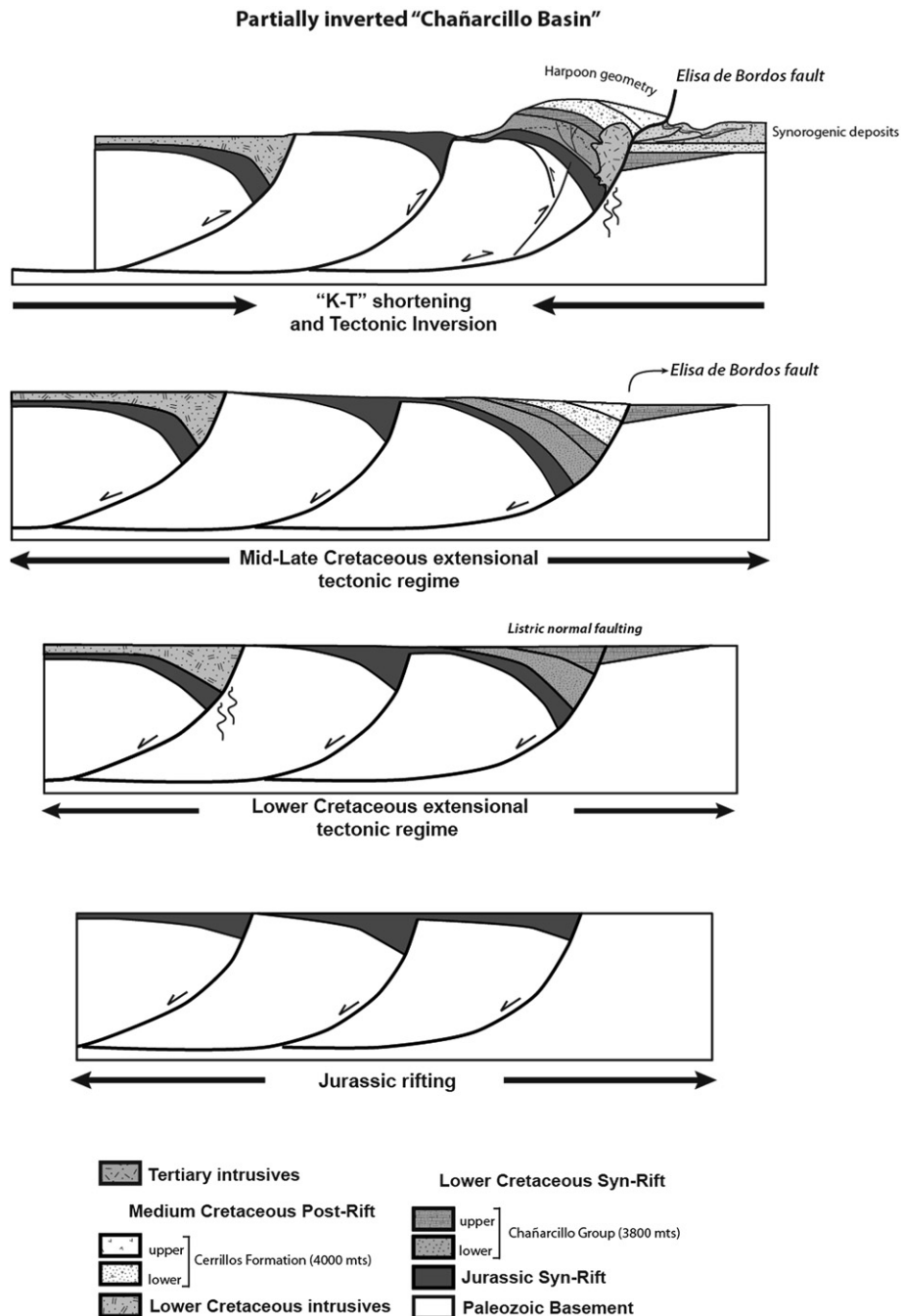


Fig. 11. A hypothetical tectonic model for the Chanarcillo Basin, from the Late Jurassic to the “K–T” Andean deformation phase.

the Hornitos Fold Belt (see synclinorium of Plate 3, Fig. 1 in Segerstrom, 1967), both originally defined by Segerstrom (1967). However, it differs from alternative structural interpretations provided by Arévalo and Mpodozis (1991), Arévalo et al. (2005a,b, 2006), who interpreted the structure of the “Tierra Amarilla Anticlinorium” as a west-vergent antiformal stack. Indeed, a series of minor west-vergent thrusts occur within the less competent layers of the Chañarcillo Group. However, they can be related to back-thrusting and accommodation structures that released the shortening accumulated in the nucleus of this asymmetrical inversion anticline.

The change from marine successions of the Chañarcillo Group to continental deposits of the Cerrillos Formation have been interpreted as the transition from the Lower Cretaceous extensional regime to the Andean compressional tectonics (Marschik and Fontboté, 2001; Maksiav et al., 2009). Arévalo et al. (2006) found $^{40}\text{Ar}/^{39}\text{Ar}$ and K–Ar ages ranging between 110 and 123 Ma in plutonic complexes intruding the Chañarcillo Group and Punta del Cobre Formation. The youngest ages obtained in these complexes (110–111 Ma) have been associated with a syn-extensional event related to the mineralization of the Candelaria Fe oxide Cu–Au deposit (Grocott and Taylor, 2002; Arévalo et al., 2006). These ages are very close to a U–Pb zircon age of 110.7 ± 1.7 Ma obtained by Maksiav et al. (2009) in volcanic rocks intercalated in the lower part of the Cerrillos Formation, suggesting that at least the lower portion of this unit accumulated before the beginning of compressional deformation. However, Maksiav et al. (2009) related the coarse conglomeratic facies of the Cerrillos Formation to a foreland basin setting.

Even though further work is needed to fully demonstrate the nature of the successions within the Cerrillos Formation, coarse conglomerates have been associated with post-rift units in other regions. Seismic reflection and stratigraphic well data from the Lusitanian Basin in the western Iberian margin, Eastern Cordillera of Colombia and Salta Basin have found coarse sandstones, conglomerates, red claystones and marls of fluvial/alluvial origin deposited in post-rift settings over syn-rift marine deposits (Alves et al., 2003; Carrera et al., 2006; Mora et al., 2009). Our structural analyses supported by field observation including the palinspastic restoration of the deformation suggest that the accumulation of the Cerrillos Formation may well be related to a post-rift thermal subsidence preceding the well documented compressional deformation in the Hornitos Formation.

On the other hand, Arévalo et al. (2005a,b), argue that the Hornitos Formation accumulated in an extensional setting controlled by the Elisa de Bordos Fault. An east-oriented dip-slip normal fault behavior for the Elisa de Bordos Fault as suggested by Arévalo (2005a,b) is inconsistent with the close relationship between the “harpoon style” of the “Tierra Amarilla Anticlinorium”, the actual position of the Cerrillos Formation, the Chañarcillo Group and the Hornitos Fold Belt and certainly the synorogenic deposits recognized within the Hornitos Formation.

Finally, according to the structural and stratigraphic relationships observed within the basin, we suggest that tectonic inversion is the fundamental deformation mechanism that allowed the interaction between younger compressive structures and the extensional Mesozoic systems in the eastern Coastal Cordillera, and increase the regional significance of extensional structural inheritance for the tectonic evolution of the northern Chilean Andes.

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